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6. AUTHOR(S)
Swanson, Randy, R.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Midtronics, Inc.
7000 Monroe Street
Willowbrook, Illinois 60527

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14. ABSTRACT
In military vehicles, many mission-critical systems rely heavily on battery power for operation. Should the batteries fail or become deeply discharged, the mission-critical systems will fail, and the batteries will not be able to start the vehicle engine, leaving the vehicle and its occupants stranded and vulnerable. Without knowing the status of the batteries, the commander is limited in his ability to keep soldiers and equipment out of harm's way. Already today, without accurate diagnostic and testing systems, battery replacement costs are a major military expense. Many batteries are replaced prematurely, while others are replaced after they have already failed and the costs of service, jump-start and replacement have already been incurred. Testing methods and equipment utilized by and available to the military today have not been successful at accurately determining failed batteries from those that are discharged and recoverable. By providing conductance-based testing and charging equipment, and outfitting vehicles with battery monitoring systems, the readiness of vehicles would be dramatically increased while reducing unnecessary replacement expenses.

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Adapting Conductance Technology for Military Application

Randy Swanson
Midtronics, Inc.

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Abstract

Advanced electronics are becoming more and more prevalent in vehicle applications. In military vehicles, communication, environmental and safety systems are mission-critical and rely heavily on battery power for operation. For example, many military ground-fighting vehicles have an operational mode called "silent watch", in which the internal combustion engine is turned off and the vehicle systems continue to operate under electric battery power to reduce acoustic and thermal emissions. Should the batteries fail or become deeply discharged, the mission-critical systems will fail, and the batteries will not be able to start the vehicle engine, leaving the vehicle and its occupants stranded and vulnerable. Without knowing the status of the batteries, silent watch operation is limited in its ability to keep soldiers and equipment out of harm's way. In addition to essential functions like silent watch, many vehicle designers are looking to add more electrical systems, replacing mechanical and hydraulic systems for improvements in cost, quality and fuel-economy. As these systems are introduced, the burden placed on the vehicle battery system increases, and the need to understand the status of the battery itself becomes critical. Already today, without accurate diagnostic and testing systems, battery replacement costs are a major military expense.

The enormous vehicle logistical issues confronting the military compound these expenses. Thousands of vehicles, most with four or six-battery configurations, sit idle for months at a time. Due to the requirements and nature of vehicle storage, and the relative inaccessibility of the battery compartment in these vehicles, little to nothing is presently known about their condition. Many batteries are replaced prematurely, while others are replaced after they have already failed and the costs of service, jump-start and replacement have already been incurred. Beyond the cost of the batteries, replacing a battery pack in some heavy-armored vehicles can take a service technician over two hours.

Testing methods and equipment utilized by and available to the military today have not been successful at accurately determining failed batteries from those that are discharged and recoverable. By providing conductance-based testing and charging equipment, and outfitting vehicles with battery monitoring systems, combat readiness of vehicles would be dramatically increased while reducing unnecessary replacement expenses.

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Preface

Team Power, part of the United States Army Tank Automotive Command located in Warren, Michigan, has identified problems associated with vehicle readiness in relation to the ability to maintain vehicle lead acid batteries in combat and tactical support vehicles. Especially during times of relative peace, the U.S. Army has thousands of vehicles that sit idle for extended periods of time. Due to the tendency of lead acid batteries to self-discharge coupled with low-rate drains during inactivity of the vehicles, there is a chance for the batteries to become severely discharged and develop a passivation condition causing the batteries to become internally nonconductive. Under these conditions, the battery is unable to accept or deliver the power required for its intended use.

In order to address this problem, the Army wished to address three main points:

1. Perform research to determine the severity or extent that battery passivation is prevalent in U.S. Army combat and tactical support vehicles.
2. Provide U.S. Army personnel with the tools to quickly, easily, and safely determine if the lead acid batteries in combat and tactical support vehicles are:
    a. Failed and must be replaced.
    b. Passivated and may be recovered.
    c. Good but simply discharged.
3. Demonstrate an in-vehicle battery monitoring system that will alert the vehicle crew to conditions of severe battery discharge or battery failure.

To accomplish these tasks, Research & Development contract W15P7T-04-C-P013 was awarded by US Army CECOM, ACQ Center, AMSEL-ACCC-RT-J, Fort Monmouth, NJ to Midtronics, Inc. of Willowbrook, IL.

The contract was executed in three phases matching the needs of the US Army. Likewise, this report will address the results of these contract efforts in three sections as follows:

1. Section 1 will address a study documenting the presence of passivation in military lead acid batteries, particularly the 6TMF battery.
2. Section 2 will address the development of a diagnostic tester/charger to diagnose and recover 6TMF batteries.
3. Section 3 will address the development of an in-vehicle battery monitoring system to warn the user that the batteries are becoming so deeply discharged that mission-critical systems may fail or the batteries may not be able to start the vehicle's engine.

1 Passivation in Military 6TMF Batteries

1.1 Summary

During analyses of reject batteries from US military vehicles, investigators discovered deeply discharged 6TMF lead-acid batteries that resisted recharge unless very aggressive charging conditions were employed.[1] It was speculated that a passivation condition was developing in good but discharged 6TMF batteries preventing their normal recharge and thereby increasing the amount of batteries returned in error. In April 2004 Midtronics, Inc., a battery management company, was contracted to investigate this phenomenon and:

- Determine the cause of the condition
- Determine the extent of its pervasiveness
- Recommend methods to reduce misdiagnosis of these and other reject batteries.

When military vehicles are stored for long periods, in many cases there remains a constant low-rate discharge on the battery system that eventually depletes the batteries of all capacity preventing starting and any other function. This slow discharge over an extended period of time can completely drain the batteries to such an extent that they do not readily recharge. In this case, the batteries are generally removed and replaced with new ones. These rejected, over-discharged batteries, often nearly new, are difficult to test and are often treated as scrap. This latter case provides the general background for batteries suffering from passivation.

The amount of active material mass in each cell of the 6TMF battery is significantly greater than the amount of electrolyte available for battery capacity. This results in the leady active materials being capable of exhausting the supply of sulfuric acid, leaving an electrolyte consisting of only water. An electrolyte void of sulfuric acid has limited conductance for charge transference and a propensity to generate hydrous colloidal lead compounds that can lead to shorting.

To conduct the analysis, Midtronics surveyed reject batteries at Fort McCoy, WI; Rock Island Arsenal, IL; North Riverside National Guard, IL; Fort Knox, KY and Fort Hood, TX.

During this investigation over 200 reject 6TMF batteries were examined at the above listed five military installations and at Midtronics' laboratory to determine their state of health. From this study it was seen that a preponderance of reject 6TMF batteries are still in serviceable condition if properly recharged and tested.

While our testing has shown that passivation in 6TMF batteries is likely to be occurring throughout the military system, its overall level is low. Less than 10% of the batteries studied had indications of passivation. With the level of other

defects projecting to be near 20%, there still appears to be a huge amount of recoverable batteries even if the passivated batteries are unable to be recharged adequately.

1.2 Introduction

Within the inherently dangerous operating environment intended for military vehicles, batteries must frequently support mission-critical functions when internal combustion engines cannot be run. The critical nature of battery systems to provide backup power during silent watch as well as subsequent starting power has been discussed earlier.

During long periods of vehicle storage there remains a constant low-rate discharge on the battery system. This discharge eventually depletes the batteries of all capacity preventing starting and any other electrical function. Over an extended period of time, this self-discharge can completely drain the batteries to such an extent that they do not readily recharge. In this case, the batteries are removed and replaced with new ones. These over-discharged batteries are often nearly new, are difficult to test, are treated as scrap and are often referred to as passivated.

The word "passivation" needs to be defined so as to provide a focus for this report. One definition found is:

> *The formation of a thin adherent film or layer on the surface of a metal or mineral that acts as a protective coating to protect the underlying surface from further chemical reaction, such as corrosion, electrodissolution, or dissolution. The passive film is very often, though not always, an oxide. A passivated surface is often said to be in a "passive state."* [2]

The 6TMF battery contains calcium-tin-lead grids and is essentially a maintenance-free version of the former battery type (6TL) that consisted of antimonial lead grids that made it necessary for the battery to receive periodic watering. It also incorporates glassmat separator envelopes to help with cycling and to further withstand vibration. The 6TMF battery is intended to achieve high levels of capacity and cranking while still retaining a rugged structure that can stand up to the physical and electrical strains of use in many military vehicles. To achieve this enhanced performance, the 6TMF battery was designed, like many high-end batteries, with a disproportionately greater amount of active material mass and structural grids in each cell with respect to the amount of electrolyte available. As a consequence of this imbalance, the leady active materials in the electrodes, at low rates of discharge, are capable of completely consuming the sulfuric acid in the electrolyte leaving only water. In other words, the low-rate, over-discharge capacity of these batteries, when new, is essentially limited by the amount of electrolyte.

The depleted electrolyte solution from an over-discharged battery contains virtually no sulfuric acid and therefore has limited conductance for charge transference. This neutral aqueous solution can also foster chemical side reactions on discharge, stand and subsequent charge that are not normal or suitable for batteries. To prevent side reactions when the battery is fully discharged or over-discharged, manufacturers often add a common ion salt, such as sodium sulfate[2], to the electrolyte solution in a concentration that will provide sufficient ions to carry current for recharge as well as preventing current-carrying lead ions and colloidal leady material from entering the neutral solution causing eventual lead shorting. From analyses run, the 6TMF appears to normally contain a 1-2% concentration of sodium sulfate[3], although this is not seen in specification.

This over-discharged condition in the 6TMF battery with no acid in the electrolyte and very low open circuit voltage is very different from that of a normally discharged battery that still contains significant acid strength and higher open circuit voltages. This distinction must be considered in the discussion of passivation.

It was theorized that in this depleted electrolyte environment a non-conducting layer could gradually develop on the positive grid blocking adequate recharge and thereby causing an apparent battery failure. This was the initial focus of the passivation investigation.

1.3 Procedures

In order to investigate the effects and extent of the phenomenon of passivation, the following procedure was followed:

A. Survey reject 6TMF batteries at various military bases to determine their condition and the extent of battery problems. Characteristics checked during survey included:
   - Voltage
   - Conductance
   - Charge acceptance
   - Electrolyte specific gravity

B. Select extremely discharged batteries for passivation testing that do not appear to have obvious defects. Batteries selected must exhibit:
   - MF construction (calcium-lead positive grids)
   - Low voltage (less than 10V)
   - Electrolyte specific gravity less than 1.030 (sodium sulfate causes deviations in the specific gravity of water)
     - Determine % sulfuric acid concentration
     - Determine % sodium sulfate
   - Low conductance (< 2 CCA with Midtronics battery testers)

- Low initial charge acceptance at a fixed voltage (<2A at 15V or <5A at 20V for 2 minutes)
- Positive electrode charging limitation with respect to a mercurous sulfate reference electrode
- Rising conductance with open circuit stand after recharge (post testing only)

C. Disassemble a limited sample of uncharged batteries that appear to exhibit passivation
    - Remove, wash and dry positive electrodes
    - Run metallographic examination of the electrode interface for passivation layers
    - Determine composition of passivation layers

C. Monitor voltage-limited recharge of various candidate passivation batteries
    - Voltage
    - Current
    - Ah input
    - Time

D. Retest passivation batteries after full recharge
    - Voltage
    - Electrolyte specific gravity
    - Conductance
    - BCI Adjustable Load Test[4]

E. Fully charge all reject batteries that are not defective
    - Determine voltage, specific gravity and conductance
    - Determine fitness for service with BCI Load Test and Midtronics testing equipment

F. Determine the extent of passivation with respect to recoverable batteries and other defects

G. Summarize findings and make recommendations

To initiate the analysis, Midtronics surveyed reject batteries at five military sites. From Fort McCoy, WI, fifteen (15) batteries were found to meet the criteria in bullet "B" above. From Rock Island Arsenal, IL, four (4) batteries were found meeting the same criteria. Batteries with limited charge acceptance were then placed on recharge for 9 hours at 14.4V with a 25A upper current limit. Each battery was monitored for voltage, current and the amount of Ah received. At the end of the charge, each battery was checked for defective cells followed by measuring the voltage and conductance. Conductance measurements were then taken over a period of time to determine if a passivation layer was continuing to break down over time. One battery in particular clearly showed a very low initial conductance that steadily rose over a period of weeks until the battery became fit for service. Most others showed a lesser degree of conductance rise.

Because of the limited number of batteries found, and that only one of the nineteen batteries was displaying passivation characteristics, Midtronics expanded its search to include the arsenal at North Riverside, Illinois. An additional seventeen batteries were obtained. These batteries had lower overall voltages and conductance readings. Many, however, still showed fairly high electrolyte specific gravities or defects. When the charge acceptance test was run, two batteries produced on the same recent date (03/04) appeared to meet the criteria for passivation. One was fully recharged at 14.4V / 25A for 9h. It recharged slowly at first and then took normal charge as the charge progressed. This was expected for a passivated battery so the mate battery was saved for disassembly.

Because the electrolyte in most of these batteries still had readings above that of water even though the battery voltage was very low, the electrolyte from sample batteries from these three locations was analyzed by titration for sulfuric acid concentration and the concentration of various soluble metallic ions. Clearly, the results show that manufacturers are adding large quantities of sodium sulfate (1-2% that increases its specific gravity) to the electrolyte in an effort to maintain conductance and to prevent shorting when sulfuric acid has been depleted. It is not surprising that one battery that contained no sodium sulfate displayed massive shorting in all cells when a recharge was attempted.

The batteries in each set with likely passivation were fully recharged and then tested via a standard Midtronics' battery tester and the BCI Adjustable Load Test (15 seconds at ½ the CCA rate) to determine acceptability for service. Most showed good performance indicating that if these batteries can be charged they will normally be good.

Because of the small number of batteries examined and the limited amount of batteries with apparent passivation (3 out of 36), the search was broadened to try to determine how pervasive the passivation condition was. Reject batteries at Fort Knox were examined and a sample of 100 batteries was sent to Midtronics for further analysis.

These were again measured to determine preliminary parameters of voltage, conductance and charge acceptance. While several candidate batteries were recharged using the same fixed voltage method described previously, most batteries were tested with a GR1 tester/charger system with progressive modifications to its software to focus on the 6TMF battery that has been stored in a low charge state.

After the GR1 tests, all batteries were fully recharged and then again tested using the BCI Load Test.

Again, very few of the batteries exhibited passivation phenomena. It is estimated that only about 3% of the batteries displayed this condition. The preponderance

of the batteries (80%) were good after fully recharging. Of the remainder, most of the batteries failed due to normal wear or defects of shorting and opens.

Because of the low incidence of apparently passivated batteries, it was decided to get yet another sample of 6TMF's, this time from Fort Hood (TX). And to make it more likely to get passivated batteries, only those with low voltage, low conductance and low charge acceptance were taken. A total of 32 batteries culled from 100 tested were shipped. It is assumed that most of the remainder of the set not taken were good and in various states of normal discharge as was the case with the previous sets.

The data clearly shows that this set of batteries was in much worse condition than the previous sets due to the greater extent of discharge and defects associated with low voltage and conductance. Good batteries made up only about 34% of the set compared to 80% in the previous full set from Knox. Passivated batteries were close to 19%.

At the same time, GR1 recovery was severely reduced and accuracy suffered due to the condition of this set. The GR1 only was able to recover 20% of the available good batteries (from 74% on the previous set) and its overall accuracy was reduced to 72% (from 81% on the previous set). Again, if the full set were tested it is projected that the results of the two sets would be similar.

1.4 Results

Of the batteries tested few appeared to be suffering from passivation. See the following table for a summary.

Location	Batteries Sampled	Passivated Batteries	% Passivated
Fort McCoy	15	1	7%
Rock Island	4	0	0%
North Riverside	17	2	12%
Fort Knox	100	3	3%
Fort Hood	100	6	6%
OVERALL	236	12	5%

Two batteries that appeared to meet the criteria for passivation were from North Riverside (NR14) and Fort Hood (H085). They were disassembled to search for physical evidence of passivation. The positive electrodes were washed to remove any soluble salts and then dried. They were then subjected to metallographic analysis to determine if there was visual evidence of a passivation layer on the positive grids.

Optical microscopy and scanning electron microscope images of the North Riverside battery showed that in the there was a clear passivation layer between the positive active material and the lead grid interface. This dense yellow layer

was identified as primarily lead monoxide by its qualitative dissolution with hot dilute acetic acid.

The battery from Fort Hood (H085) was also submitted for analysis. Following the same techniques used in the first analysis, the interface between the positive grid and active material was examined.

Again clearly seen was a layer between the grid and the active material that appeared to be a passivation layer similar to that seen in NR14. However, when the samples were subjected to a hot dilute acetic acid treatment, only a layer very close to the grid seemed to be affected.

Believing that the treatment was not vigorous enough, an extended 30-minute soak of the samples was performed. Again, the dense yellow layer between the grid and the active material refused to completely disappear indicating the layer was not primarily lead monoxide.

When the samples were again polished, there emerged a non-porous white layer between the grid and the active material that appeared to be lead sulfate. To verify this, the samples were subjected to a qualitative hot soak in a solution of ammonium acetate, which completely removed the layer.

1.5 Conclusions

During this investigation, 236 reject 6TMF batteries were examined at various military installations and at Midtronics' laboratory to determine their state of health. From this study a picture is seen that a substantial majority of reject 6TMF batteries are still in serviceable condition if properly recharged and tested.

Due to the nature of their use patterns, military vehicles that are stored for an extended time yield batteries that are severely depleted in electrolyte strength. These batteries cannot be tested easily and are therefore often scrapped and replaced with new ones even though they may still be recoverable.

Positive electrodes in lead-acid batteries exposed to neutral aqueous solutions can produce passivation layers between the lead grid and the positive paste. This layer is normally an intermediate oxide of lead such as lead monoxide or combinations with lead sulfate. This passivation layer can impede the initial recharging of a battery to the extent that it appears that the battery is defective due to low charge acceptance. If a limited charge is continued, this passivation layer gradually breaks down allowing increasing charge to occur—eventually yielding more normal charging conditions.

While most batteries with this condition recover quickly to give normal battery power, some display lingering effects of low conductance due to the passivation layer that can be seen for many weeks after recharge. Due to the length of the

induction time to remove the passivation layer, this battery type would obviously be scrapped.

Although our testing has shown that passivation in 6TMF batteries is likely to be occurring throughout the military system, its overall level is low. Less than 10% of the batteries studied had indications of passivation. With the level of other defects projecting to be near 20%, there still appears to be a huge amount of recoverable batteries even if the passivated batteries are unable to be recharged adequately.

Clearly there are ways to avoid passivated batteries. From the analysis of the batteries it is obviously seen that newer 6TMF batteries can completely consume their entire available electrolyte acid concentration thereby putting the battery in a condition to accelerate the formation of passivation layers. Neither redesigning the battery to give less capacity by using less active material nor increasing the volume of the battery to accommodate more electrolyte is very palatable.

The only way left is to limit the amount of over-discharge so that the battery never depletes its electrolyte strength. This will clearly involve much more stewardship of the batteries than is done at present.

For a complete and more detailed report on the subject of passivation, contact Midtronics, Inc. for a copy of Document No.: DAA-IM-146 Technical Summary Report on Passivation in Military 6TMF Batteries.

1.6 References

[1] Dr. Henry Catherino, Electrochemist, RDECOM-TARDEC, *Conference call with Midtronics*, May 7, 2004

[2] D. Berndt, *Maintenance-Free Batteries, 2nd Edition, 1997*, p. 82

[3] Electrolyte Analyses, Hammond Industries, Hammond, IN, June 2004

[4] Battery Council International (BCI), *Storage Battery Technical Service Manual (2002)*, p. 20-21

2 Diagnostic Tester/Charger

2.1 Summary

As discussed in Section 1, there are two major modes in which military batteries become deeply discharged. One mode is through the required activity called "silent watch" whereby internal combustion engines are shut off to reduce acoustic and infrared emissions, or signatures. The second is through battery self-discharge and vehicle parasitic loads that occur when a vehicle is not operated for extended periods of time. In either case, a decision must be made to recharge or replace the batteries. Currently, the service technician has not had the diagnostic tools required to make an intelligent decision. As a result, many batteries that can be recovered are actually replaced, or failed batteries end up being replaced only after investing considerable time in attempting to recover them. Thus an intelligent, interactive diagnostic tester/charger is needed to perform the required testing with an appropriate charging cycle.

Midtronics developed the necessary tool for just this very task. Using a commercial off-the-shelf (COTS) diagnostic conductance charger, called the GR-1, as a starting point, Midtronics modified the internal hardware and software for the military application. After performing a repetitive cycle of code modification and testing, Midtronics was able to adapt this commercial unit to successfully meet the needs of recovery and recharging of the large capacity military battery. To prove this technology works, Midtronics was able to recover a number of military batteries that were destined for the scrap pile and returned them to service.

2.2 Introduction

During the study to document the presence of passivation in military lead acid batteries, particularly the 6TMF battery, it was seen that a significant number of batteries were being rejected because of deep discharge. The batteries can become deeply discharged as a result of undergoing an extended "silent watch" action where vital vehicle systems rely solely on the batteries to provide the necessary power. The batteries can also become over discharged through a long period of time of vehicle inactivity. In either case, the result is a battery that has insufficient power to start the vehicle's engine, thereby negatively impacting the vehicle's readiness. If allowed to continue in this state of deep discharge, the risk of passivation and total battery failure increase dramatically.

As observed in our research on passivation, the occurrence of passivation is actually quite small. It was observed that a significant percentage of the rejected batteries were simply discharged and could be recovered for return to service. In order to make that decision, a diagnostic tool that can test for the presence of passivation layers is needed along with a charger capable of recovering deeply

discharged batteries. Midtronics has developed the GR-MIL prototype tester/charger to perform both functions.

2.3 Procedures

The GR-MIL prototype diagnostic conductance charger was developed from the commercial off-the shelf (COTS) GR-1 charger that is supplied to the automotive industry. This unit uses conductance technology to perform diagnostic testing on batteries before, during and after the charging cycle. This means that time is not wasted trying to recover batteries that have internal failures and cannot be effectively recharged.

To increase the usefulness of this charger on military vehicles, internal hardware was added to allow the charger to charge at 24Vdc. Note, however, that this is a manual charge function only, meaning that battery diagnostics and intelligent charging algorithms are not followed. The scope of this contract did not allow for the development of intelligent charging algorithms during 24Vdc charging. It is hoped that Midtronics, Inc. will be tasked to develop an intelligent 24Vdc charging algorithm under a future effort.

The software inside the intelligent charger was modified along several lines. First the algorithm was optimized from small automotive batteries to the larger capacity 6TMF military battery. As stated in the passivation study, the design of the 6TMF battery is such that the 6TMF battery has a disproportionately greater capacity of active material mass and structural grids in each cell with respect to that of the available electrolyte. In other words, the low-rate, over-discharge capacity of these batteries, when new, is essentially limited by the amount of electrolyte. To account for this, the algorithm was modified for the lower voltage and charge acceptance that these deeply discharged batteries may exhibit.

Another change to the algorithm was to add an intended overcharge feature to aid in better mixing of the electrolyte and to remove charge imbalance between cells.

At the end of the charge cycle, the diagnostic charger is designed to perform a final test to ensure the charged battery is ready for service. Due to the critical mission the battery performs in military applications, the approval requirements the battery must meet were raised above that of a commercial automotive battery.

2.4 Results

During our research regarding the passivation of batteries, a sample of 100 reject batteries from Fort Knox were sent to Midtronics suspected of being passivation candidates. These were measured to determine preliminary parameters of voltage, conductance and charge acceptance. Most were then tested using the

GR-MIL prototype with the progressive software modifications described above to focus on the 6TMF battery that has been stored in a low charge state. After GR-MIL prototype tests, the batteries were fully recharged and tested again using the BCI Load Test. Approximately 80% of the batteries were good after fully recharging. Normal wear failures or defects of shorting and open circuits accounted for most of the remainder of the batteries. The rapid charging GR-MIL prototype tester/charger was 81% accurate compared to a BCI Load Test after a lengthy full recharge.

An additional sample of 32 batteries was sent to Midtronics from Fort Hood. These batteries had more stringent selection requirements of low voltage, low conductance and low charge acceptance to make it more likely to get passivated batteries. Two of these batteries were removed from the lot due to mechanical defects and a third was disassembled for laboratory metallographic examination. The remaining 29 batteries were subjected to GR-MIL prototype analysis followed by a full recharge and load testing. Even though this sample was selected because of an increased likelihood of finding passivated batteries, the GR-MIL prototype was able to recover 20% of the sample batteries. It is assumed that the remaining population of 68 batteries would have been recovered normally.

Because the GR-MIL prototype was able to recover a significant number of batteries that various Army posts had placed in the scrap pile, Midtronics contacted a local National Guard installation that gladly accepted 44 of the recovered 6TMF batteries. Some time later, when Midtronics personnel visited that facility with regards to the iBMS, we were pleased to observe recovered batteries still bearing our inventory numbers in vehicles being readied for service in Iraq.

2.5 Conclusion

Starting with a commercial diagnostic conductance tester/charger, the GR-1, Midtronics was able to modify the unit to satisfactorily diagnose deeply discharged and failed batteries. From a sample of 100 batteries being rejected by Fort Knox, the GR-MIL prototype was able to recover roughly 80 batteries with an overall accuracy of 81% compared to a BCI Load Test. In a much more severe test of 29 batteries rejected from Fort Hood selected for their probability of exhibiting passivation, the GR-MIL prototype was able to recover about 20% of the available batteries with an overall accuracy of 72% compared to a BCI Load Test. Again, it is assumed that the majority of the batteries not sent, approximately 68, would have been recoverable thereby giving results comparable to the Fort Knox testing.

Per the contract requirements, a quantity of 5 GR-MIL prototypes were shipped to TACOM Warren who forwarded them to undisclosed US Army positions in Operation Iraqi Freedom. These 5 units are being used in real world conditions

by real US Army troops on real military vehicles. Feedback received from the field include comments such as:

- "This will save my unit a lot of money on replacement batteries not to mention critical downtime for vehicles that can now be back in the battle quicker"
- "A very simple machine to operate. Nothing too hard to figure, very simple instructions."
- "Of the five batteries, we save 4 of the 5. The ones in the truck it saved both batteries. And at this time that is one thing (batteries) hard to get."
- "If I can save the money, the charger will pay for itself."
- "Thanks for the battery charger it works like a champ"
- "The machine is very user friendly"

3 IBMS – Intelligent Battery Monitoring System

3.1 Summary

It was shown in Section 1 of this report that batteries which are allowed to reach a state of deep discharge are more likely to develop passivation layers between the lead grid and the positive paste. This passivation layer can impede the initial recharging of a battery to the extent that it appears that the battery is defective due to low charge acceptance. As discussed earlier, many military ground-fighting vehicles invoke a silent watch mode for extended time periods that can easily cause a battery system to become depleted if the operator is not notified of the real-time battery condition. Deeply discharged batteries will not provide the energy required to maintain critical functions including starting the vehicle engine. Although not currently present in US Army vehicles, the technology exists to provide real-time in-vehicle battery monitoring. Midtronics has developed a real-time in-vehicle battery monitoring system for commercial vehicles using conductance technology. The commercial application is called inGEN. Based on this inGEN platform, Midtronics modified the system for application on military specific vehicles. To demonstrate the function of the system called MIL112, Midtronics has delivered proof of concept prototypes to Team Power, TACOM.

3.2 Introduction

It is obvious that advanced electronic applications are becoming more and more prevalent in vehicle applications. Communication, environmental and safety systems are mission-critical systems that rely on battery power for operation, especially during silent watch operation in which the main engine is switched off to reduce thermal and acoustic signatures. Should the batteries fail or become deeply discharged, not only will mission-critical systems fail, but the batteries will not be able to start the vehicle engine. Without knowing the status of the batteries, silent watch operation is limited in its ability to keep soldiers and equipment out of harm's way. In addition, many vehicle designers are looking to add more electrical systems. As these systems are introduced, the burden

placed on the vehicle battery increases and the need to understand the status of the battery itself becomes even more critical. Currently, battery replacement costs are a major military expense. Real-time battery monitoring will not only prevent the vehicle and crew from being stranded as a result of silent watch operation, but it can also reduce the chances of battery damage due to over discharge

3.3 Procedures

Midtronics based the MIL112 Intelligent Battery Monitoring System (iBMS) on the commercial inGEN system. InGEN is a microprocessor-based automotive battery sensor that continuously measures battery voltage, battery temperature, charge/discharge current and conductance. Using these parameters, inGEN calculates the battery's real-time State of Charge and State of Health. Depending on the application, these parameters can also be used to calculate capacity, available power, remaining operating time as well as other useful status indicators.

When fully charged, a new battery will have a high conductance enabling full power to be delivered to electrical system loads. However, as a battery ages, the current carrying structure of the battery can corrode and deteriorate lowering the its conductance and adversely affecting its ability to deliver power. In addition, conductance can be used to detect cell defects such as shorts and open circuits that can cause a battery to fail. Thus conductance, coupled with other pertinent data, provides a reliable indication of the battery's cranking State of Health.

The Display Interface Module (DIM) has been designed to look for State of Charge and State of Health information from both inGEN sensors. It then signals the driver's display to report the lower SOC and SOH values. A MIL112 system malfunction is indicated to the driver by blanking out everything on the display with the exception of the SOC lettering at the top of the display. Should this occur, all systems connections should be checked to ensure both inGEN sensors are reporting to the DIM.

State of Charge provides a measurement of the available energy in the battery at a given moment in time, taking into account capacity deterioration, temperature and the present or average discharge rate. This calculation is essential to ensure that mission-critical functions can continue without severely discharging the battery and stranding the crew. The MIL112 version has an LED bar graph displaying State of Charge to provide the driver with a clear indication of the amount of energy available in the battery under the prevailing conditions (temperature, discharge rate, battery condition, etc.). This bar graph consists of two red LEDs, three yellow LEDs, and three green LEDs as viewed from left to right. Currently the values for the LED display at each State of Charge range are shown in the following table:

SoC	LED 0	LED 1	LED 2	LED 3	LED 4	LED 5	LED 6	LED 7
0-7%								
8-15%								
16-24%								
25-40%								
41-57%								
58-74%								
75-82%								
83-91%								
92-100%								

These values were assigned by Midtronics as an initial estimate of what the user would desire, having finer resolution at either end of the bar graph. However, these values are software driven and could be changed according to customer desires.

At the right end of the State of Charge bar graph are two additional red LEDs. For the purpose of this system, these two red LEDs are not considered part of the bar graph. They are treated as a single LED and are called Voltage Fault. The Voltage Fault LEDs will be lit whenever the system voltage, defined as the sum of the voltage from the 2-inGEN units is above a preset threshold of 30.00 Volts or the voltage of either inGEN unit is above 15.00 volts. These two red Voltage Fault LEDs are intended to mimic the red range on the right end of the current voltmeter MS24532/A-A-52508 by indicating an overcharging condition. These thresholds are software driven and could be changed according to customer desires.

Since inGEN technology can monitor the battery's real-time State of Health and its decline over time, the useful life of the battery can be predicted. The driver's display supplied in the MIL112 version includes LEDs to indicate that batteries are reaching the end of their useful life and LEDs indicating a battery failure, which should be replaced. This will assist the crew in replacing worn or failed batteries in the safety and convenience of the depot or maintenance area instead of possibly becoming stranded on the battlefield.

Each inGEN is capable of recognizing battery faults, such as a short or an open. When a battery fault has been detected a message will be sent to the Display Interface Module (DIM). When the DIM receives notification of a fault, it will flash the Check Battery LED. In addition, each inGEN will send a calculated State of Life value once every 12.8 Seconds. If the State of Life falls below a threshold initially set at 50%, the Check Battery LED will flash. If no battery faults are

detected by any inGEN, and the State of Life returned by all batteries is above the threshold, the Check Battery LED will not be illuminated.

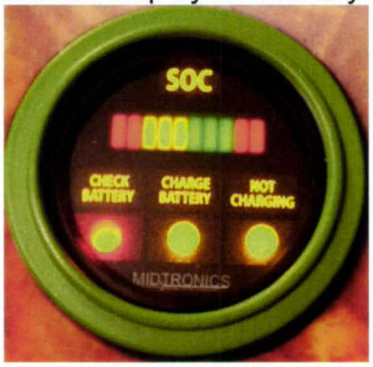
The Charge Battery LED will flash when the displayed State of Charge falls below a threshold of 25%. When the displayed State of Charge is above another pre-determined limit, currently set at 25%, the Charge Battery LED will be turned off. These limits can be separated to provide for hysteresis for the LED. The purpose of this feature is to indicate to the vehicle driver that he may need to run the engine for an additional period to time to ensure the battery has an adequate State of Charge before shutting down the vehicle.

Each inGEN unit is capable of determining if the batteries it is connected to are charging. The inGEN will notify the Display Interface Module (DIM), if the charging current is less than 1 amp. The DIM will flash the Not Charging LED any time either inGEN indicates a battery is receiving less than 1 amp charging current. The Not Charging LED will be turned off, only when both inGEN units indicate they are receiving 1 amp or more charging current. A flashing Not Charging LED may indicate:

- A fault is present in the charging system.
- The engine speed is too low for full alternator output.
- The vehicle electrical loads are exceeding the alternator's ability to meet those loads and charge the battery.

A flashing Not Charging LED may be expected in situations such as silent watch where power is being required but the alternator is not running to provide that power. Note: When the Master Switch is first turned on, the DIM will assume there are no charging problems.

Figure 1: iBMS display for military vehicles



The inGEN system was designed for commercial vehicles having a single 12-volt battery. To accommodate 24-volt military vehicles having either two 12-volt batteries in series or four 12-volt batteries in a series/parallel configuration and with the possibility of a 12-volt tap in either configuration, several modifications were required.

- The algorithm programmed into the battery sensor had to be modified to account for the large capacity 6TMF military lead acid battery. Various charge and discharge curves had to be developed to characterize and mathematically model the battery's performance.
- The algorithm also had to be modified to deal with the fact that we could now have multiple batteries in parallel effectively increasing the battery size, but with power loss through parallel cabling.
- The commercial inGEN was designed for a 12-volt system. Midtronics considered altering the inGEN for use on a 24-volt system until it was discovered that many of the vehicles could have 12-volt power taps. This would indicate that many of the battery packs would be out of balance, i.e. the 0-12 volt battery(s) having a different State of Charge than the 12-24 volt battery(s). To handle this, Midtronics decided to have a battery sensor for each 12-volt segment of the battery pack. This required the development of the Display Interface Module, which receives battery parameters, both measured and calculated, from each sensor and makes the proper determination of information to be displayed to the vehicle operator.

3.4 Results

Midtronics, Inc. has delivered a number of proof of concept prototype MIL112 systems to Team Power TACOM Warren, MI. However, there is no provision in this contract for the installation and testing of these units on actual military vehicles. Midtronics is confident that the MIL112 iBMS will provide the real-time in-vehicle battery monitoring that is needed by today's combat and tactical vehicle teams to yield continuous diagnostics of the battery system and to prevent deep discharge of the batteries during vehicle operation.

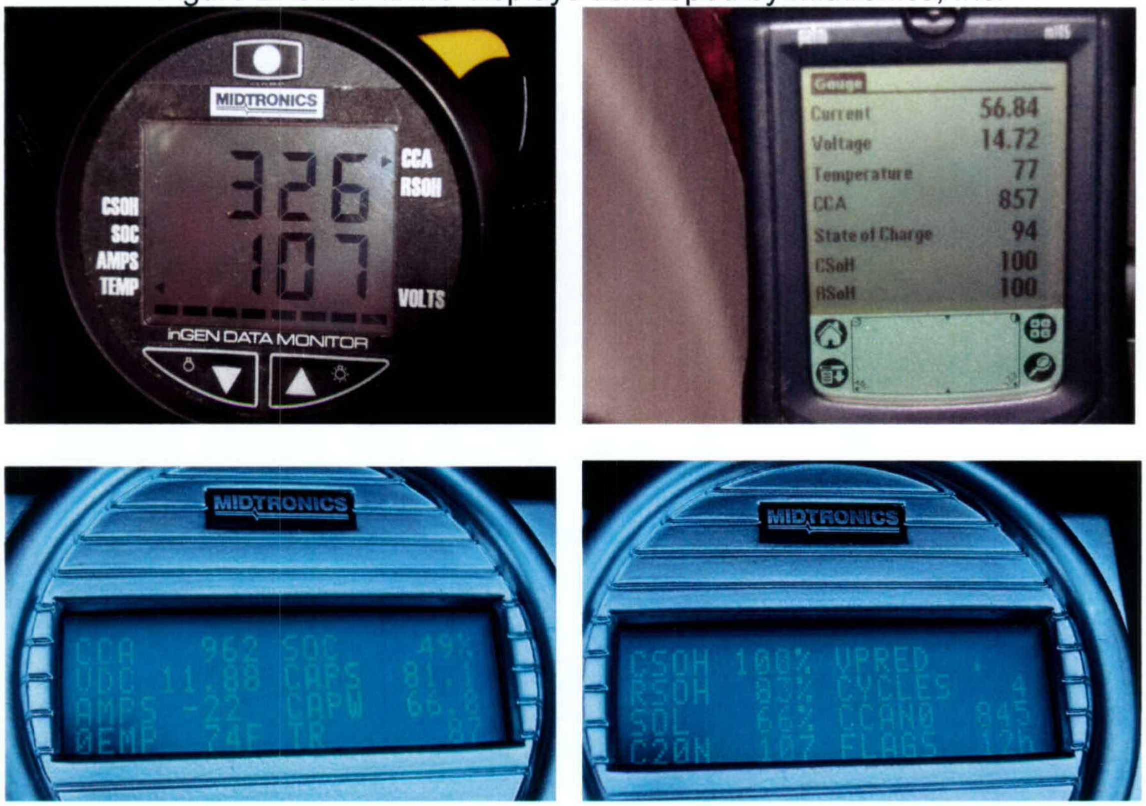
3.5 Conclusion

Midtronics has been informed that Team Power has plans in place to perform actual vehicle testing of the MIL112 iBMS. Midtronics, Inc. looks forward to providing installation assistance and support during this test. Midtronics is confident that once the system is tested, crews will quickly come to appreciate the real-time knowledge this system provides regarding the condition of their batteries. It is also suspected that once the user becomes familiar with the system he will actually desire information that the system can additionally provide. The current driver's display is a result of a previous effort between Midtronics and TACOM on a specific combat vehicle application. The information selected and the way in which it is displayed was requested by TACOM to be similar to the existing voltmeter and reduce the burden on the soldier by not requiring him to process the meaning of numbers that could be presented. However, should it be desired, the iBMS can provide the following information to the operator:

- Battery Voltage
- Amps (charge or discharge)
- CCA under various conditions
- % Cranking
- Estimated Cranking Voltage
- Battery Temperature
- Amp Hours Discharged
- Estimated Open Circuit Voltage
- State of Charge
- Working Capacity
- Present C20 Capacity
- Rated C20 Capacity
- Equivalent 50% Duty Cycles
- Nominal CCA
- Average Discharge Amps
- Discharge Time Remaining
- State of Life
- Cranking State of Health
- Reserve State of Health
- Battery Defect Status (Shorts, Opens, Overcharge, etc.)

To prevent operator information overload, Midtronics desires U.S. Army input to determine what information is most useful to them. Midtronics Inc. can arrange the information to be displayed in the user's specified format as demonstrated in Figure 2.

Figure 2: Other iBMS displays developed by Midtronics, Inc.



Use of the MIL112 iBMS will certainly reduce the number of deeply discharged batteries in actively-used vehicles. Vehicles that stand idle for extended periods of time, however, will continue to require periodic inspection to eliminate deep discharge from occurring due to vehicle parasitic loads and self-discharge. Whether this is accomplished by turning on the MIL112 systems or by using a hand held tester has yet to be determined, but is a necessary part of the US Army's total battery management plan.